HUMAN ENVIRONMENTAL HEAT TRANSFER SIMULATION WITH CFD – THE ADVANCES AND CHALLENGES

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ABSTRACT

The modelling and prediction of human thermoregulatory responses and comfort have gone a long way during the past decades. Sophisticated and detailed human models, i.e. the active multi-nodal thermal models with physiological regulatory responses, have been developed and widely adopted in both research and industrial practice. The recent trend is to integrate human models with environmental models in order to provide more insight into the thermal comfort issues, especially in the non-homogeneous and transient conditions. This paper reviews the logics and expectations of coupling human models with computational fluid dynamics (CFD) models. One of main objectives of such approaches is to take the advantage of the high resolution achievable with the CFD, to replace the empirical methods used in the human models. We aim to initiate debates on the validity of this objective, and to identify the technical requirements for achieving this goal. A simple experiment with 3D human models of different sizes and shapes is also reported. Initial results shows the presence of arms may be important. Further experiments are required to establish the impact of size and shape on simulation result.

INTRODUCTION

There are three detailed human thermoregulation models being widely used. The IESD-Fiala model was developed by Dr Dusan Fiala in the late 90's at the Institute of Energy and Sustainable Development, De Montfort University, UK (Fiala, 1998). The 65MN model was developed by the group led by Professor Shin-ichi Tanabe at Waseda University, Japan (Tanabe et al. 2002, the model was first reported in 2001). The Berkeley model was developed at the Center for Environmental Design Research, University of California, Berkeley, USA (Huizenga et al, 2001). Despite being implemented separately, all three models can find their roots in the original Stolwijk model (Stolwijk et al, 1971), which is still in use, although report on further development has not been seen for a long time.

It would be interesting to compare the three human models in detail. Unfortunately, this is not in the scope of this paper. Briefly, under the skin, the concepts and the formulae of the three models are very similar – these are multi-segment, multi-node human models that encompass both thermal and thermoregulatory processes of the human body. One of the major differences is the data sources that have been used in validation. The Fiala model was extensively validated against a wide range of experimental data from the literature. The Berkeley model also incorporated results from further experiments carried out in UC, Berkeley. The validation approach of the 65MN was unclear.

In terms of functionality and applications, the three models are more different. The Fiala model and the 65MN model are "research" models, which are text-based and running from the command line. This sometimes makes them easier to be integrated in other applications, such as environmental simulation software and CFD. Both models enjoyed wide adoption in both academic and industrial fields. The Berkeley model has a much friendlier user interface, as well as a "body builder" which allows users to adjust many internal parameters on the GUI. The Berkeley model includes also a local (dis-)comfort model developed by Zhang (2003).

The more recent trend is to integrate human models with environmental modelling tools such as CFD. It is anticipated, by doing this, more details of the interaction between the body and its ambient environment can be revealed. Compared to the level of details modelled inside the human body, the human model still relies on empirical and simplified methods to calculate heat exchange between the body and the ambient environment. On the other hand, the technology of Computational Fluid Dynamics (CFD) has matured in recent years. It was marked by a range of commercial CFD software packages being widely adopted in both engineering and scientific works. The intriguing question is can we gain more knowledge in the underlying mechanism of human thermal comfort by combining the power of both models.

Several attempts have been reported. The automotive industry has been using the CFD and human model to design comfortable cabin space. Since occupant's contribution to the thermal environment of the cabin of a car is considerably less than the weather, one-way link from the CFD tool to the human model (therefore, the human model acts like a multi-sensor) is normally sufficient. Such examples can be found in (Han et al. 2001, Tanabe, 2004). Murakami et al. (2000) reported one of the early attempts for full integration. A vase-shaped smooth figure was used to represent the human body in the CFD, which was coupled with Gagge's 2-node thermal regulatory model. The CFD code simulated the flow field for the given temperature boundary conditions. Meanwhile the 2-node model provided prediction of skin temperature distribution corresponding to the local sensible heat loss values calculated by the CFD. This approach was replicated by Al-Mogbel (2003), who used FLUENT (a CFD package) and a human figure consisted of six cylinders.

Intuitively, the simplified 3-D model or the 2-node human model would not satisfy the requirement for studying human response to heterogeneous environment. Tanabe et al. (2002) reported integration of the 65MN model with CFD and radiation code. A 3-D model of an unclothed male body was used. Steady-state results were shown to include the effect of solar (short wave) radiation. Convective heat transfer from the body, however, was calculated from empirical heat transfer coefficients, rather than from CFD simulation. As a result, the CFD code was mainly used to calculate the impact of human body on the environment. Other works include (Omori et al., 2004), in which CFD code coupled with Fanger's model was described. The latest development on this front was carried out by Yang and colleagues (Yang et al, 2007, Zhang and Yang, 2008), who integrated Fiala model with a realistic 3D figure in CFX (a commercial CFD package). However, some fundamental questions were raised during the investigation.

These questions include "why", "what", and "how". The answer to "why we would need integrated CFD and human models" seems simple: on the human side, we want more resolution and accuracy in the calculation of heat transfer at the boundary; on the environment side, we want the environmental quality (e.g. thermal comfort) to be evaluated by human response rather than thermometer reading. However, the proof that incorporating CFD improves the accuracy of the existing human model is yet to be seen. On the other hand, the human models were developed to evaluate (relatively) stable and uniform environment. Can it handle the extra resolution provided by CFD?

The second question is what aspect of the human model is unsatisfactory and can be replaced with the CFD model. A simple answer is that CFD should handle the convective, evaporative and radiant heat exchange calculation outside the boundary of human body. However, where is the boundary, the clothes surface, the skin surface, or the boundary of inner skin (for evaporation)?

The last question is how we validate the integrated models. Few of the experimental studies, whose data have been used in validating the human models, has provided enough details for validating CFD simulations or coupled models. Do we need a completely new set of experiments for validation purpose?

This paper aims to provide some initial discussions on the issues with using CFD to simulate heat transfer process at the surface of human body. We first look at how environmental heat exchange is presently handled by the human models; then use a simple experiment to discuss the impact of the choice of 3D models in CFD.

ENVIRONMENTAL HEAT TRANSFER

The different mechanisms of heat exchange between the human body and its environment have been well investigated and documented by researchers in different fields of study linked to human thermal comfort. The methods and equations used in simulating the environmental heat exchange can be found in many publications including ISO and ASHRAE standards. In this paper, we base our discussion on the equations and symbols used in the Fiala model (Fiala, 1998).

In general, the total flux of heat loss $\boldsymbol{q_{sk}}$ [W/m^2] at the body surface is a sum of heat exchange by convection ($\boldsymbol{q_c}$), by radiation ($\boldsymbol{q_r}$), by irradiation from high-temperature sources (e.g. the sun) ($\boldsymbol{q_{sR}}$), by evaporation of moisture from the skin ($\boldsymbol{q_e}$), and by respiration via convection ($\boldsymbol{C_{rsp}}$) and evaporation ($\boldsymbol{E_{rsp}}$). In general, the total heat flux $\boldsymbol{q_{sk}}$ passing the surface of a peripheral sector is equivalent to the sum of individual heat exchanges given in *Equation 0* as:

$$q_{sk} = q_c + q_r - q_{sR} + q_e + (C_{rsp} + E_{rsp}) \qquad \textbf{(0)}$$

Convective heat transfer

Giving the mean ambient air temperature $\boldsymbol{T_a}$[°C]**,** the air Velocity $\boldsymbol{v_a}$ [m/s] and the surface temperature $\boldsymbol{T_{suf}}$ [°C], the local convective heat transfer coefficient ($\boldsymbol{h_c}$ [W/m^2/K]) can be calculated with *Equation 1***.**

$$h_c = \sqrt{a_{nat}\sqrt{T_{sf} - T_a} + a_{frc}\, v_a + a_{mix}} \qquad \textbf{(1)}$$

Note that $\boldsymbol{h_c}$ is a function of the location on the body, the temperature difference between the body surface and the ambient air ($\boldsymbol{T_{sf}}$ **-**$\boldsymbol{T_a}$), and the effective air speed $\boldsymbol{v_a}$ [m/s]. The coefficients of natural, forced and mixed convection ($\boldsymbol{a_{nat}}$, $\boldsymbol{a_{frc}}$ and $\boldsymbol{a_{mix}}$) were derived from the experimental results of Wang (1990). Their ($\boldsymbol{a_{nat}}$, $\boldsymbol{a_{frc}}$, $\boldsymbol{a_{mix}}$) values for each body part can be found in Table A.1 in (Fiala, 1998). Other human models use $\boldsymbol{h_c}$ from difference sources. For example, the $\boldsymbol{h_c}$ used in the 65MN model is based on (Ichihara et al, 1997). The Convective heat flux $\boldsymbol{q_c}$ is then calculated using *Equation 2*:

$$q_c = h_c (T_{sf} - T_a) \qquad \textbf{(2)}$$

Evaporative heat transfer

The local evaporative heat transfer coefficient $\boldsymbol{U_{E,cl}}$ [W/m^2/Pa] is obtained using the local values of the overall moisture permeability index ($\boldsymbol{i_{cl}}$), the overall intrinsic clothing thermal insulation from the skin to the clothing surface ($\boldsymbol{I_{cl}}$) of individual local clothing layers applied to the local surface area factor of a garment $\boldsymbol{f_{cl}}$ and the local convection coefficient $\boldsymbol{h_c}$, and the Lewis Ratio $\boldsymbol{L_a}$ [K/Pa] for air resulting in *Equation 3*:

$$U_{E,cl} = \frac{L_a}{\sum_{j=1}^{m}\left(\frac{I_{cl}}{i_{cl}}\right)_j + \frac{1}{f_{cl}\cdot h_c}} \quad \textbf{(3)}$$

The mean ambient vapour pressure $\boldsymbol{p_a}$ and the skin vapour pressure $\boldsymbol{p_{sk}}$ are then used in conjunction with the evaporative coefficient $\boldsymbol{U_{E,cl}}$ to calculate the evaporative heat loss $\boldsymbol{q_e}$ as shown in *Equation 4:*

$$q_e = U_{E,cl}(\, p_{sk} - p_a \,) \quad \textbf{(4)}$$

It is clear that the calculation of evaporative heat transfer is dependent to the calculation of the convective heat transfer coefficients; therefore, the accuracy of $\boldsymbol{h_c}$ has a significant impact on the overall accuracy of the total heat loss calculation.

Radiant heat transfer

The surface temperature $\boldsymbol{T_{sf}}$ [K] and the mean radiant temperature of the envelope $\boldsymbol{T_{sr,m}}$ [K] are used to calculate the local radiant heat transfer coefficient $\boldsymbol{h_r}$ [W/m^2/K] as in *Equation 5*. Radiant heat flux $\boldsymbol{q_r}$ [W] is calculated with *Equation 6*.

$$h_r = \sigma\, \varepsilon_{sf}\, \varepsilon_{sr}\, \Psi_{sf\text{-}sr}\left(T_{sf}^2 + T_{sr,m}^2\right)\left(T_{sf} + T_{sr,m}\right) \quad \textbf{(5)}$$

$$q_r = h_r \cdot (\, T_{sf} - T_{sr,m} \,) \quad \textbf{(6)}$$

Where $\boldsymbol{\sigma}$=5.67$\cdot$10^{-8} [W/m^2/K^4] is the Stefan-Boltzmann constant, $\boldsymbol{\varepsilon_{sf}}$ and $\boldsymbol{\varepsilon_{sr,m}}$ are the emissivity values of the local body surface sector and the mean surrounding surfaces, respectively. $\boldsymbol{\Psi_{sf\text{-}sr}}$ is the corresponding view factor between the local body surface sector and the surrounding surfaces.

Proximate values of $\boldsymbol{\varepsilon_{sr,m}}$, $\boldsymbol{\Psi_{sf\text{-}sr}}$, and $\boldsymbol{T_{sr,m}}$ are often used in the applications of the human model, due to the difficulty in calculating the precise view angles between each segment of body surface and that of the surrounding surfaces.

Solar radiation

The amount of heat absorbed at a sector surface because of irradiation from high temperature sources (sun, fireplaces, etc.) is taken into account in the heat balance of superficial body element sectors by the term $\boldsymbol{q_{sR}}$, which is given as:

$$q_{sR} = \alpha_{sf}\, \Psi_{sf\text{-}sr}\, s \quad \textbf{(7)}$$

Where $\boldsymbol{\alpha_{sf}}$ is the surface absorption coefficient and depends on the colour of the covering material, $\boldsymbol{S}$ is the radiant intensity, and $\boldsymbol{\Psi_{sf\text{-}sr}}$ is the view factor between the sector and the surrounding short wave sources, including direct, diffusive and reflected solar radiation. It is often impractical to calculate precise intensity and view factor of each source, in which case proximate values are used in the equation.

Respiratory heat loss

Two empirical equations derived by Fanger (1972) are used to calculate the evaporative and convective elements of respiratory heat loss (see *Equations 8-1* and *8-2*)

$$E_{rsp} = 4.373\int q_m dV\left(0.028 - 6.5\times10^{-5} T_a - 4.91\times10^{-6} p_a\right) \quad \textbf{(8-1)}$$

$$C_{rsp} = 1.948\times10^{-3}\int q_m dV\left(32.6 - 0.066\, T_a - 1.96\times10^{-4} p_a\right) \quad \textbf{(8-2)}$$

The total respiratory heat loss is dependant to the whole body metabolism ($\int q_m dV$ [W]), the ambient air temperature ($\boldsymbol{T_a}$ [°C]) and the ambient vapour pressure ($\boldsymbol{P_a}$ [Pa]).

Equation map and empirical parameters

Figure 2 shows the diagrammatic representation of the calculation of the total heat flux $\boldsymbol{q_{sk}}$ at the body surface in the Fiala Model. The circles represent the *Equations 0* to *8*. The rectangular shapes identify variables and coefficients/parameters. Equations with empirical or proximate parameters or coefficients are gray-shaded. Detailed CFD and radiation models, (despite that most of the CFD models are still semi-empirical), should be used to replace those shaded equations. In this paper, we focus on the convective heating transfer models.

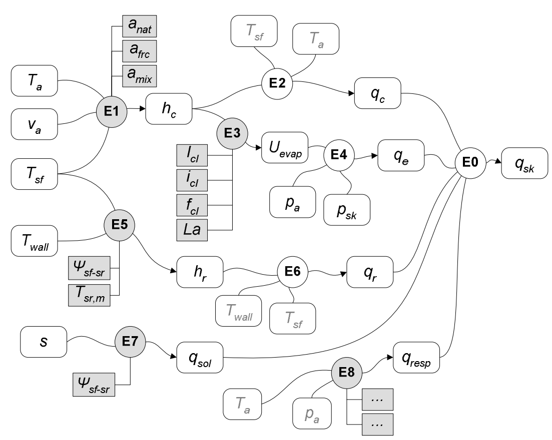


Figure 1. Equation map of human ambient heat transfer

CONVECTIVE HEAT TRANSFER

Since we are aiming to improve the accuracy and resolution of the computation of environmental heat transfer on the human body by using CFD, it is useful to identify the areas that have the potential of improvement. Radiant heat transfer is a clear candidate, because by using the well-established ray tracing methods, the detailed shapes, position and texture information can be taken into account. It is not straightforward, however, to incorporate ray-tracing simulation to the existing human models. We will reserve this topic for a separate report. In this paper, convective (and evaporative) heat transfer calculation is the focus.

Convective Heat Transfer Coefficient

h_c is often used in the comparison of the experimental and simulation results. Equation 2 provided the definition of the coefficient. Ideally, h_c should be independent to the temperature difference between the surface and the ambient air. This is not the case, however, in most indoor (comfort) environmental conditions. Consensus is that h_c is correlated to the temperature difference to the power of 0.25 (e.g. in *Equation 1*), when effect of natural convection is significant. As a result, it is difficult to compare the h_c's from different sources where the precise conditions were not given.

This is an important issue, since most of the human models use virtually the same methods to calculate the convective heat flux, and, subsequently, the evaporative heat flux. The only difference is how h_c is derived, and on which set of experimental data it is based. For example, the *Equation 1* in the Fiala model is based on the results from Wang et al. (1990); whereas the corresponding equation in the 65MN is based on the results reported by Ichihara et al (1997). Figure 2 shows the mean convective heat transfer coefficient of the human body from a number of published experimental studies over the past decades. The difference from one set of data to another can be as high as 100%.

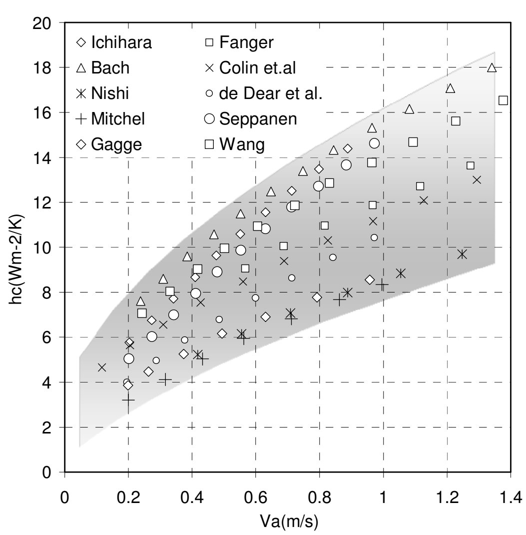
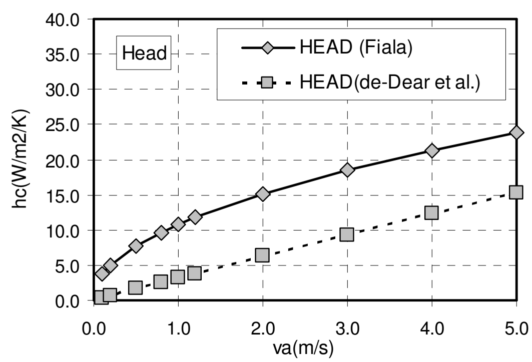


Figure 2 Whole body convective heat transfer co-efficient (h_c) from various published works (Ichihara et al,1997; Gagge, 1986; Seppanen et al, 1972; Mitchell, 1974; Colin and Houdas, 1952; Fiala, 1998; de Dear et al, 1997; Fanger, 1971; Bach,1991; Nishi,1973)

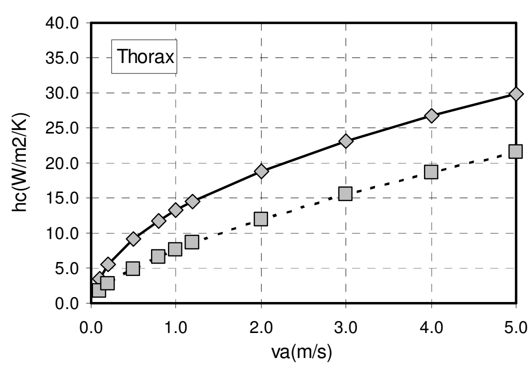
Arguably, since h_c is dependent to temperature difference, divergence is expected from different experiments where different surface temperature and its control strategy, as well as air temperature are used. If *Equation 1* is correct, however, 100% deviation in h_c is equivalent to at least 16°C deviation in temperature difference, which is highly unlikely. The source of this uncertainty remains unknown.

Local Coefficients

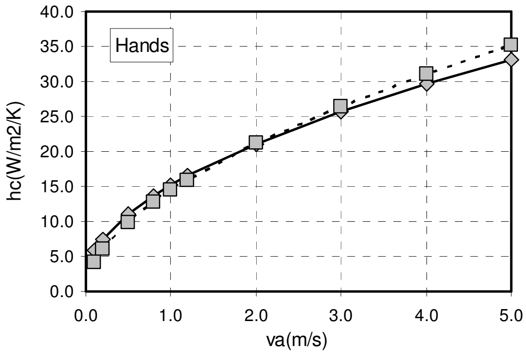
More comparison has been done between the experimental results on local convective heat transfer coefficients reported by de Dear et al. (1997) and the values use in the Fiala model (1998). The surface temperature and the air temperature in the Fiala model have been set to reflect the experimental condition. In all body segments except hands, the local h_c from de Dear et al. is significantly lower than that is used in the Fiala model. Figure 3 (a), (b) and (c) show the local coefficient at head, torso, and hands, respectively. Understandably, the posture of the body and the position of the limbs would have significant impact on local heat transfer. It is even harder to achieve any agreement between experiments than the mean heat transfer value for the whole body. The good agreement shown in Figure 3 (c) can be simply a coincident.



(a) Head



(b) Torso



(c) Hands

Figure 3 Local convective heat transfer coefficients (Fiala 1998, de Dear et al. 1997)

Sources of Divergence

Speculatively, the possible causes of the divergence (including uncertainty) in the experiments can include:

- Selected surface air temperature setting – since h_c is temperature-dependent at low air speed, the temperature difference between the body surface and the ambient air can be a significant factor.
- The control mechanism and accuracy of the mannequin used in the experiment – related to the point above, some mannequins offers individual surface temperature control for each body part, whereas others provide only uniform temperature or heat flux.
- Uncertainty of equipment, including the wind tunnel, transducers, and the sensors in the mannequin – the uncertainty in measurement can aggregate. Parameters such as turbulence intensity are not commonly measured in the experiments.
- The impact of size, shape and position of the mannequin – different mannequins have been used in the experiments. Apart from the difference in size and shape (male/female) of the mannequins, the exact posture and the position of the limbs are often omitted in the report. However, this could be the most important factor in evaluating local heat transfer coefficients.

It would be very useful to review all experimental conditions of the data shown in Figure 2, in order to establish the uncertainty range of the published h_c's. In the meantime, the shaded area in Figure 2 can be used as a consensus uncertainty range. However, the reliability of this uncertainty range is highly questionable because collectively, only 10 experiments (data points) were used. These represent a very small sample giving the number of variables that are potentially involved. To fill in the gaps, CFD simulations can be used to study the potential impact of some of the variables, e.g. size, shape, and position.

COMPARISON OF CFD MODELS

In theory, experimentally validated Computational Fluid Dynamics (CFD) models can be used to fill in the missing points in a dataset, as well as to cross-validate experimental results. Some fundamental works, however, are necessary for establishing the requirement for the benchmark CFD models.

The Requirements

The benchmark CFD models of human body can be used by researchers in studying environmental heat transfer around the body in various circumstances. Such models have to be numerically stable and validated against the existing (or new) experimental data in strictly controlled laboratory conditions. The geometry of the model must be easily adjustable for evaluating the effect of size/shape/position, whereas the baseline mesh quality must be specified to ensure accuracy and consistency. The following questions have to be answered by anyone who endeavour to develop such a benchmark model.

1. What level of details of the shape of the human body should be modelled?
2. What size, shape and posture of the body should be adopted; and what is the impact?
3. Should clothed or nude body be used?
4. Which boundary condition (heat flux or surface temperature) of the CFD model should be used; is it necessary to use realistic temperature distribution rather than a uniform skin temperature?
5. What specifications of the test chamber/wind duct should be given?
6. What is the minimum mesh quality required for numerical stability and solution accuracy?

Some initial works on the impact of sizes and shapes are reported here.

Size and Shape

In the reported CFD simulations involving human body, models that have a wide variety of sizes and shapes were used. These models can be roughly put in three categories: simplified shapes (Murakami et al., 2000, Al-Mogbel, 2003), standard human mannequins (male and female) (Tanabe et al. 2002, Omori et al., 2004, Sorensen and Voigt, 2003), and realistic models (Yang et al., 2007, Zhang and Yang, 2008).

Theoretically, even if only the mean heat transfer coefficient of the whole body is of concern, the (relative) sizes of the body parts have an impact on the result. However, the deviation in body sizes is small compared to the uncertainty range of both the numerical and the experimental data. Similarly, the shapes of the body parts have significant impact on the local heat transfer coefficients, e.g. the protruding parts such as the chin, the hands, and the breasts of a female body often show elevated h_c's in numerical results. On the mean heat transfer coefficient of whole body, however, the impact of these parts is limited due to (1) relatively small skin area of these parts, (2) some of the parts (e.g. breasts) are covered by clothes in normal circumstance, and (3) change of body posture and the direction of air movement may reduce h_c values of these parts.

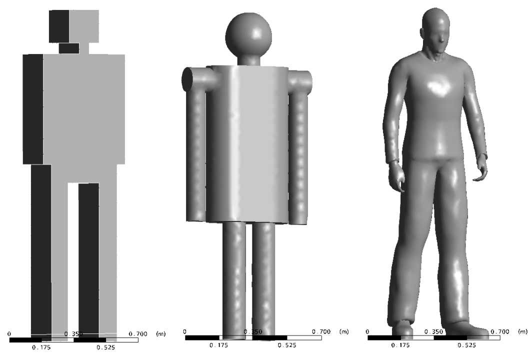


Figure 4 Three shapes to compare

In this paper, three CFD models of human body are compared: a very simple block-shaped body (the Block Man), a sphere/cylinder-shaped body with arms (the Tin Man), and a more realistic shape of a male body in casual clothes (the Digital Mannequin, see all models in Figure 4). The Digital Mannequin has the height of an average European male with a clothed surface area of 2.2m^2. We did not check the sizes or the total surface areas of the simple models. They may be regarded as random samples of individuals in particular outfits. Simulations were carried out with these models standing upwind under a range of ambient air velocities (0.1 – 1.4m/s) at 25°C. The other CFD settings (e.g. mesh quality and boundary conditions) for the models are equivalent.

Initial Result

The results for the models with a uniform surface temperature of 33.0 °C are shown in Figure 5, along with the whole body convective heat transfer coefficients from Fiala (1998) and de Dear et al. (1997).

The result is interesting yet surprising. Firstly, the Digital Mannequin and the Tin Man appeared to agree well with the results from de Dear el al., despite that the experimental result was obtained with a 12°C temperature gradient rather than the 8°C for the CFD cases. Secondly, the results for the Digital Mannequin and that for the Tin Man are hardly distinguishable, whereas the average h_c for the Block Man is significantly lower. This could be attributed to coincidence; and more sizes and shapes should be tested. However, an inspection of the local distribution of the convective heat transfer coefficient (see Figure 6) may suggest that the presence of arms is important.

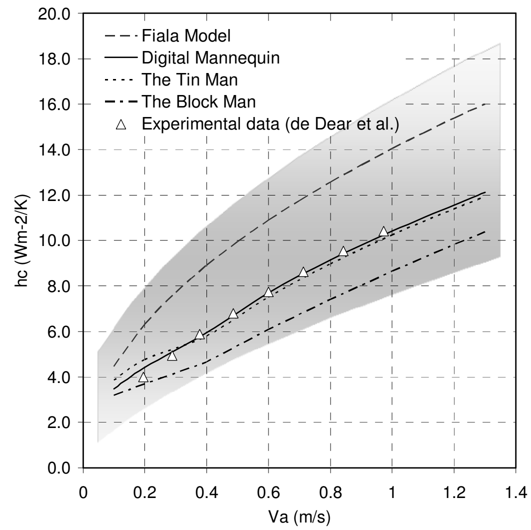


Figure 5 Three shapes to compare

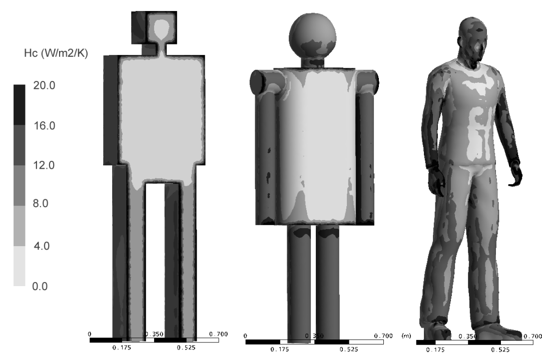


Figure 6 Distribution of local h_c on the 3 models

CONCLUSION

This paper presents some thoughts about issues of human environmental heat transfer simulation. In particular, we discussed uncertainty sources in both numerical and experimental methods. Wide divergence was observed in the published experimental results. The possible sources of the divergence have yet to be identified. This situation makes it difficult to develop and validate a coupled human-CFD model. In theory, however, a reliable CFD model can be used to cross-validate existing experimental results.

This paper took the first step: three CFD models with different level of geometric complexity were compared to identify the significance of the impact of sizes and shapes. The initial results are interesting but inconclusive. A systematic approach is needed for further investigation. For example, parametric analyses on size, geometry, orientation, posture, and boundary conditions have to be conducted. To achieve this, collaboration between research groups are preferable, which subsequently requires a set of commonly accepted specifications on the CFD model of the human body. This may be the most important step towards the future of the coupled models.

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